Assimilation of AIRS CO_2 Observations with EnKF in a Carbon-Climate Model

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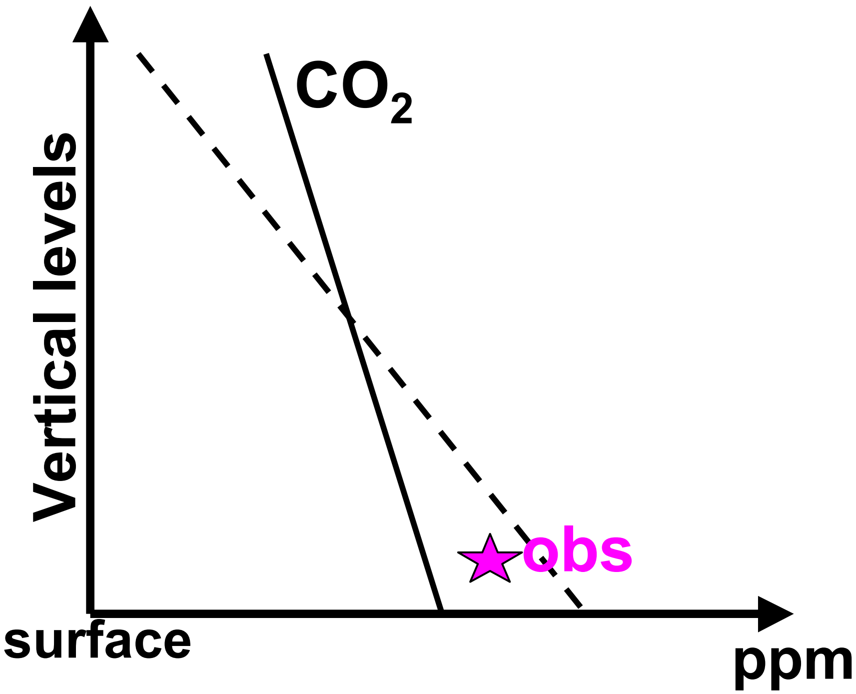
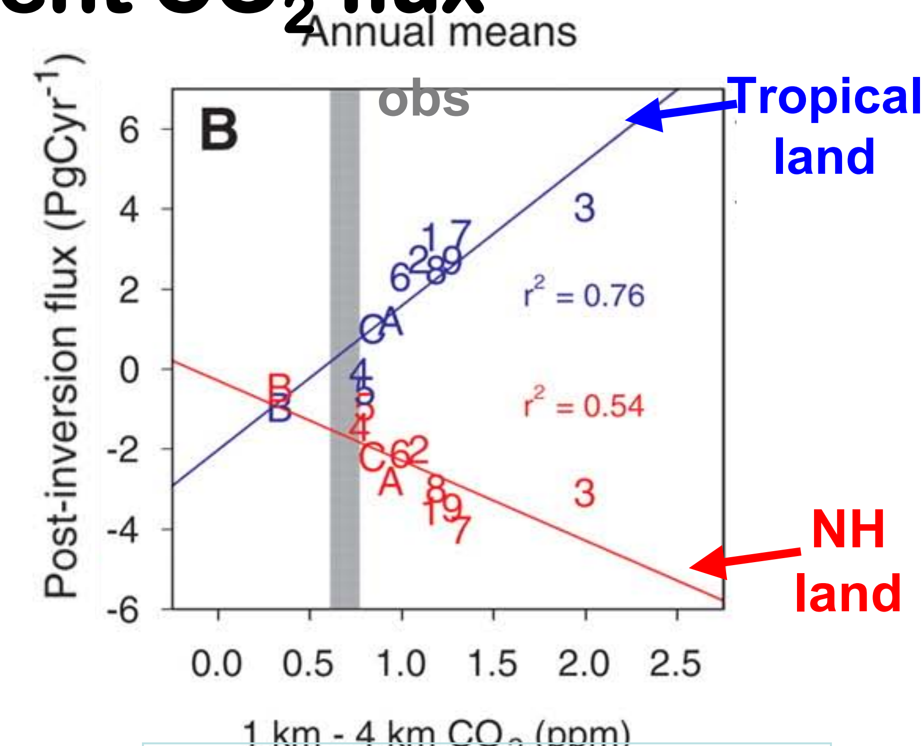
Different CO_2 vertical gradient forecasts give different CO_2 flux





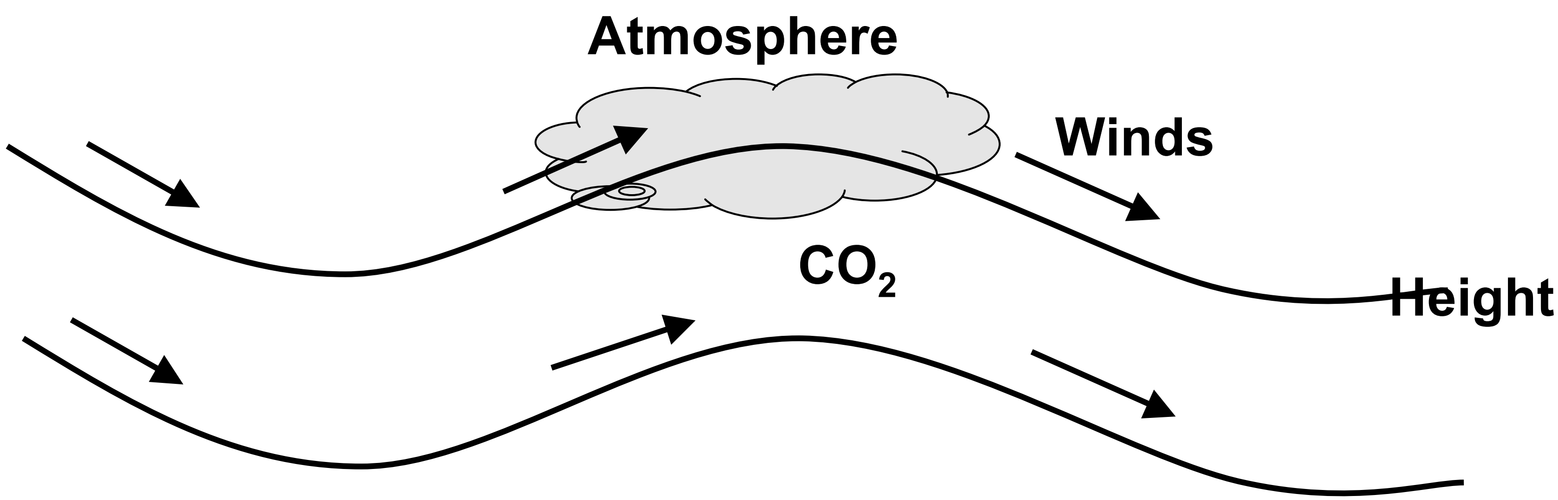
Stephens et al., 2007, *(Science)*

- Numbers and characters are different transport models.

=> Important to have accurate vertical mixing in the model;

=> Accurate 4-D (x, y, z, t) CO_2 fields.

Meteorology fields & CO_2

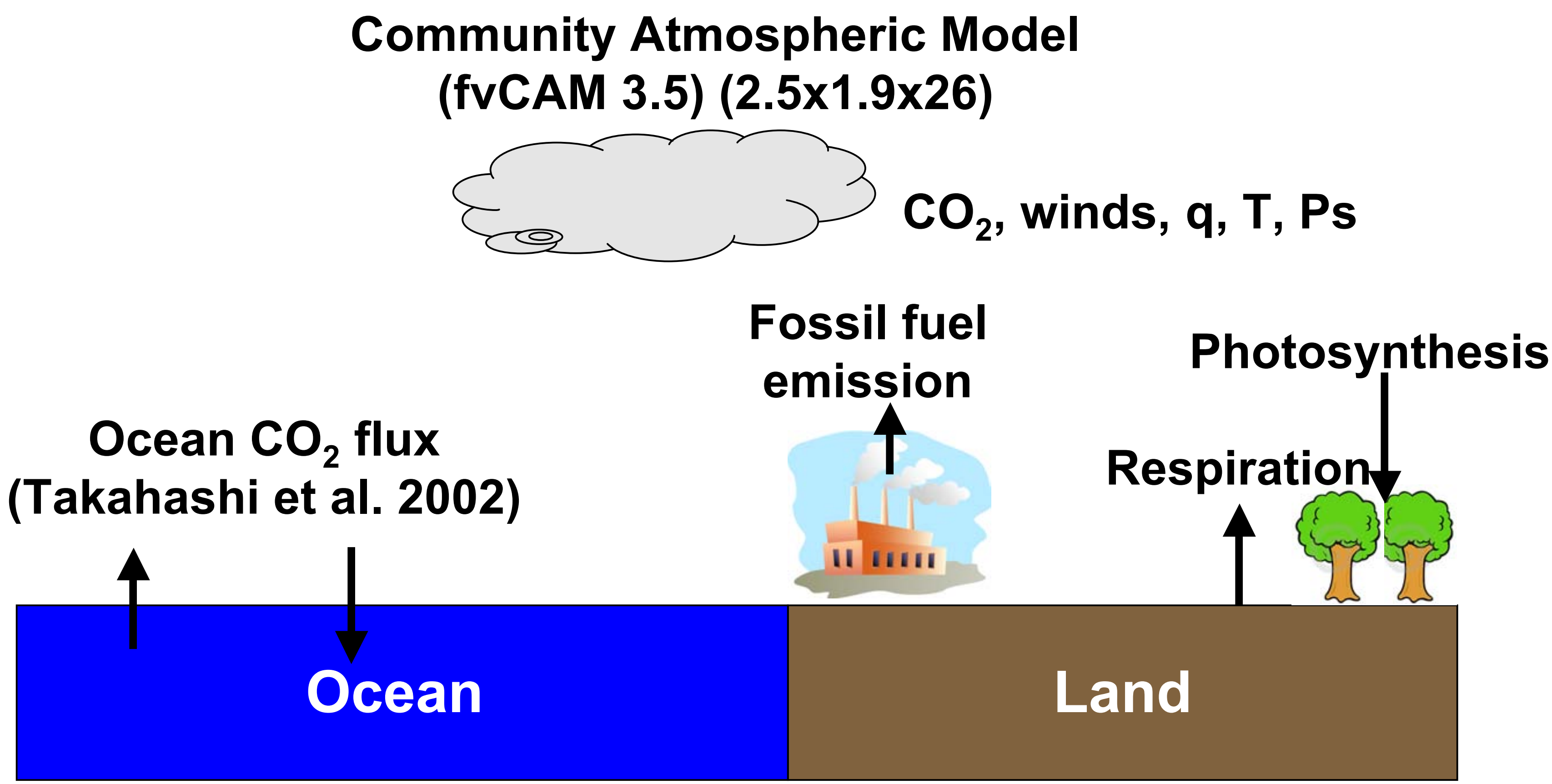


- Offline transport models have been used.
- The initialization meteorology fields are from either reanalysis products (usually 6-hourly) or off-line dynamical model;
- The vertical mixing has large uncertainty;
- Single realization of meteorological field.

Research Goals

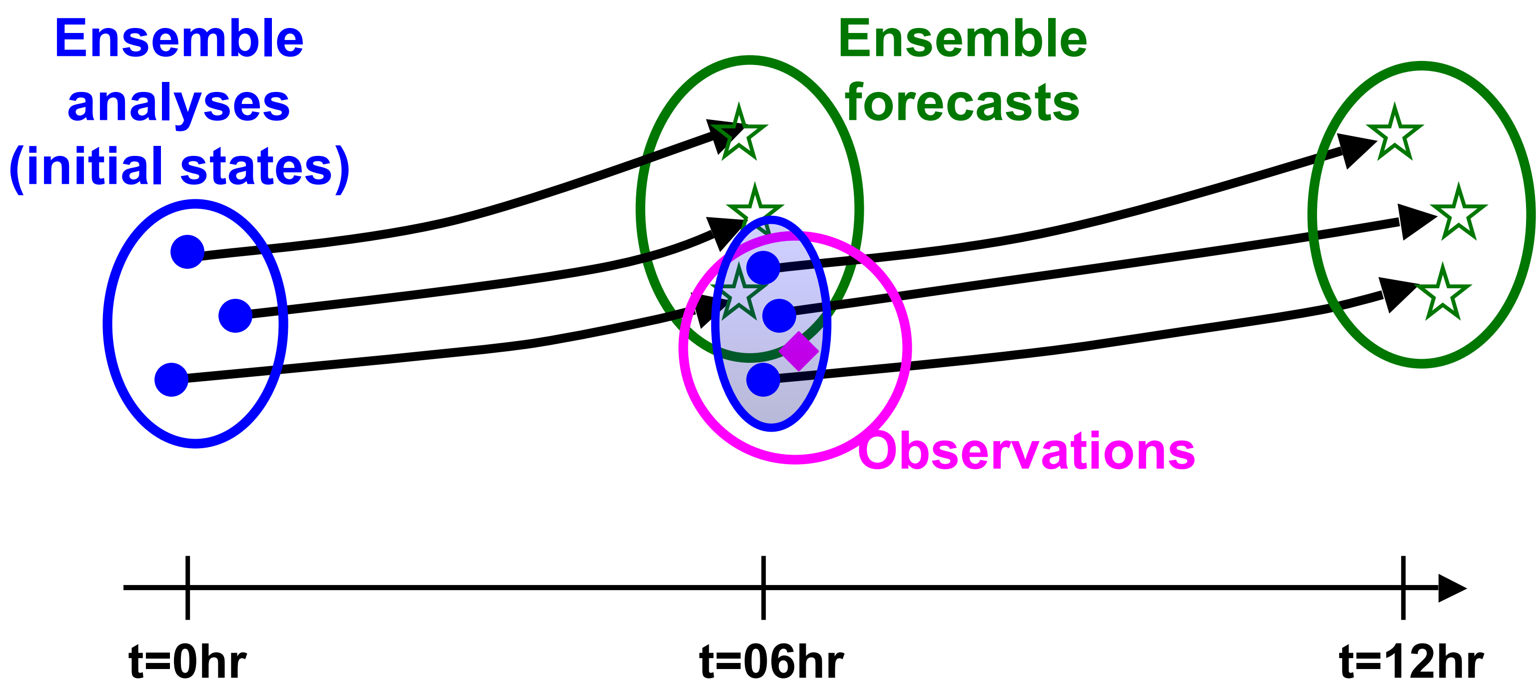
- Generate **6-hourly 3-D (x, y, z) CO_2 fields** by assimilating **CO_2 and meteorological observations** with **full GCM**

Carbon-Climate Model



- CO_2 is transported as a tracer;
- Vertical mixing is updated every 30 minutes;
- Land carbon flux: 6-hourly flux from biogeochemical model.

Ensemble Kalman Filter (EnKF) process



- Forecast error changes with time;
- Obtain ensemble analyses.

CO_2 Observation Operator

- Model forecast x^b is CO_2 vertical profile;
- AIRS CO_2 is column-weighted Volume Mixing Ratio (vmr);

=> observation operator: interpolate x^b to obs location & calculate model forecast column-weighted CO_2 vmr.

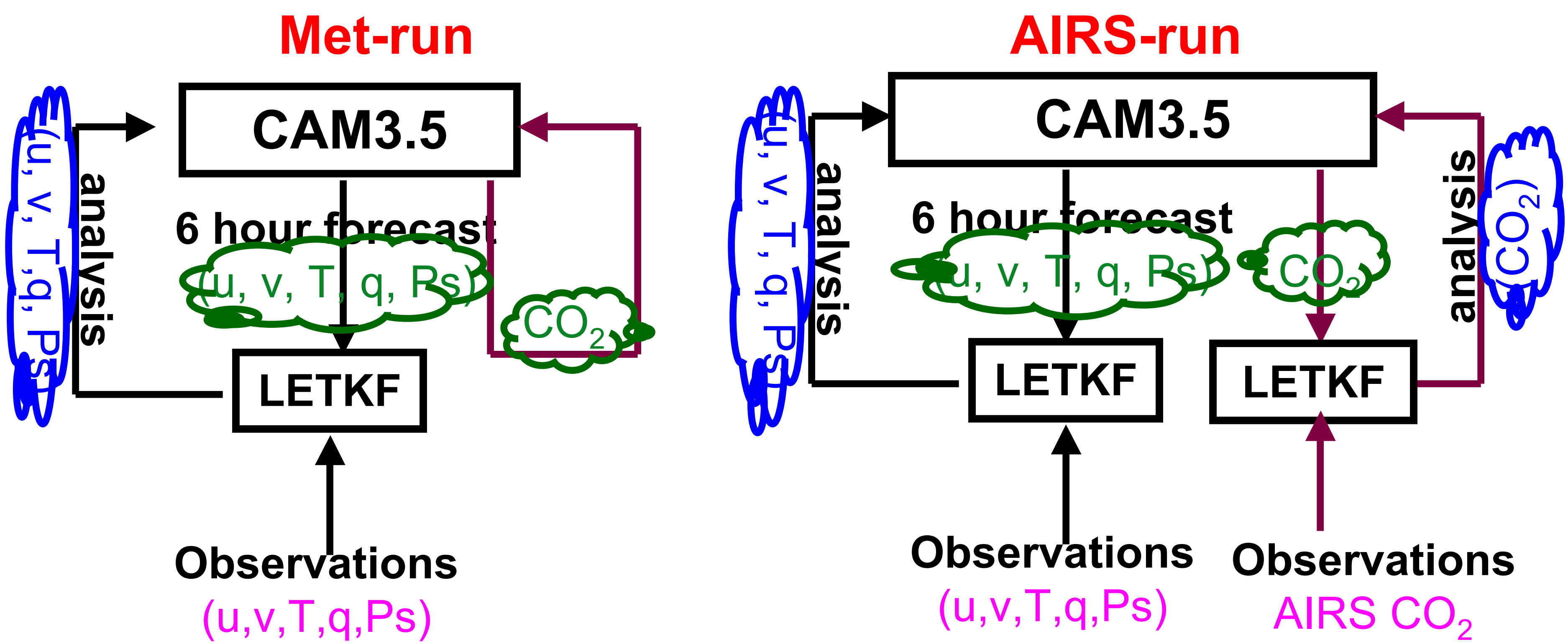
$$\underbrace{\mathbf{y}^b}_{\text{model forecast "obs"}} = \underbrace{\underbrace{\mathbf{A}}_{\text{avg kernel}}{}^T \Big(\underbrace{S}_{\text{spatial interpolator}} \Big(}_{\text{obs operator}} \underbrace{\mathbf{x}^b}_{\text{model forecast}} \Big)\Big)$$

Assimilation experiments

- Met-run: assimilate raw meteorological observations (10^6 observations)

- **AIRS-run: assimilate AIRS CO_2 observations in conjunction with meteorological observations.**

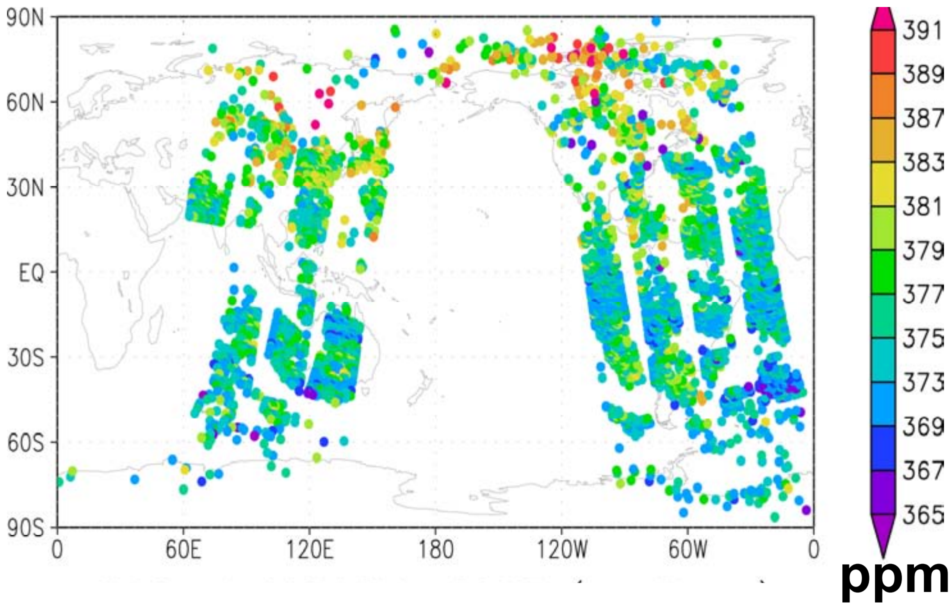
The impact of AIRS CO_2 assimilation on 6-hourly CO_2 3D (x, y, z) fields



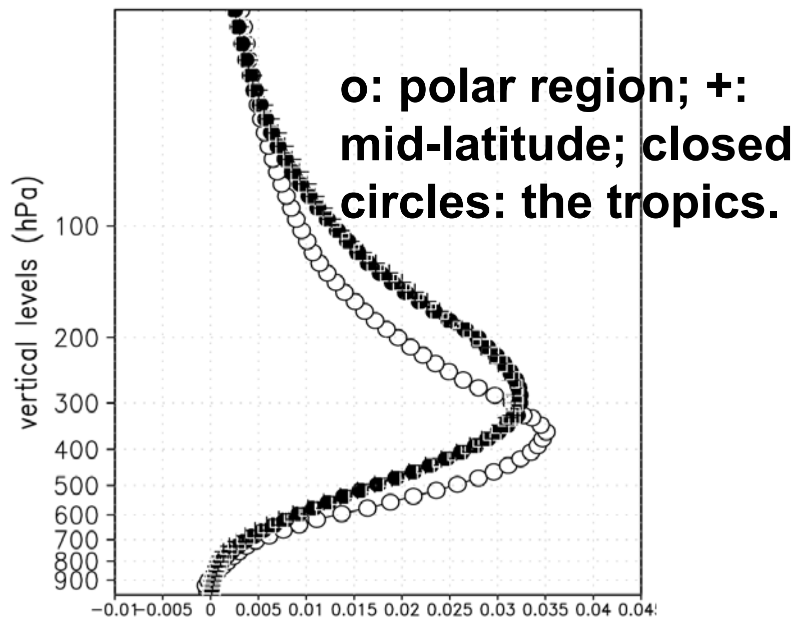
- AIRS-run: AIRS CO_2+met obs; Met-run: only met obs.
- The year of 2003.
- Prescribed surface CO_2 flux forcing.

More than 2000 AIRS CO_2 within 6 hours; more sensitive in the middle troposphere

AIRS CO_2 at 18Z01May2003 (+/-3hour)



AIRS averaging kernel

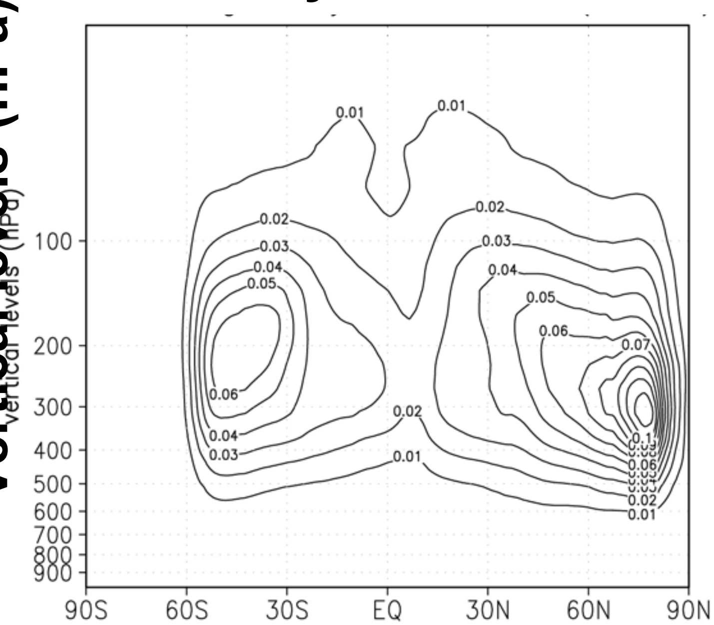


- Averaging kernel: the sensitivity of AIRS CO_2 to CO_2 at each vertical level.

Analysis corrections to CO_2 forecast peak at the similar levels as the peak of the averaging kernels

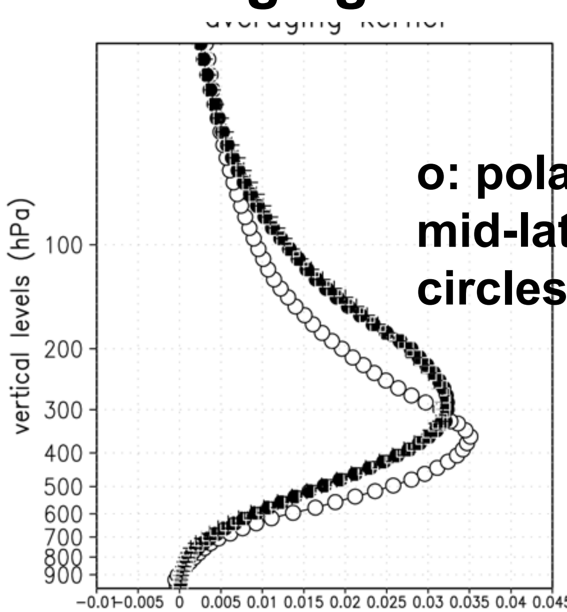
Time-averaged (10 months) absolute analysis corrections

Vertical levels (hPa)



90°S **0°** **90°N**

Averaging Kernel



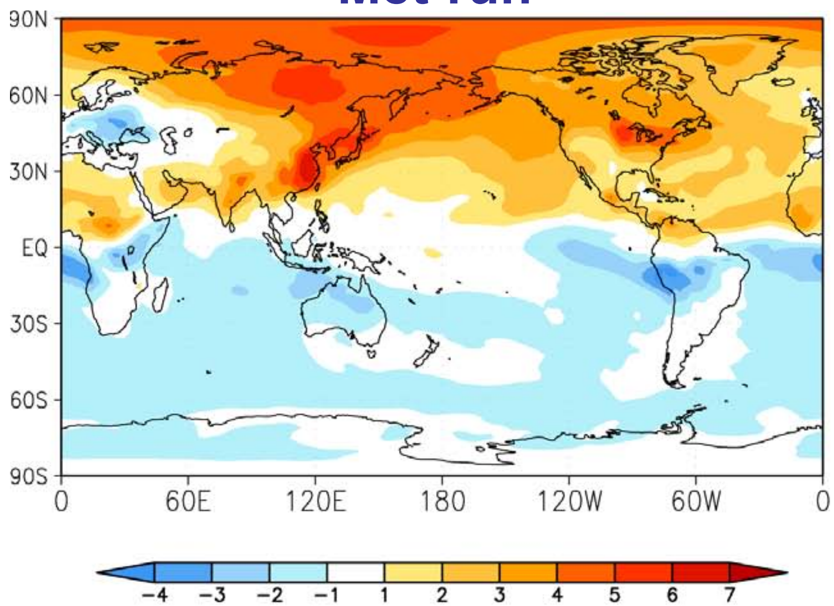
o: polar region; +: mid-latitude; closed circles: the tropics.

- **No CO_2 observations beyond 60ºS.**

Assimilating CO_2 adjusts CO_2 vertical gradient

May 2003: CO_2(850hPa)-CO_2(400hPa)

Met-run

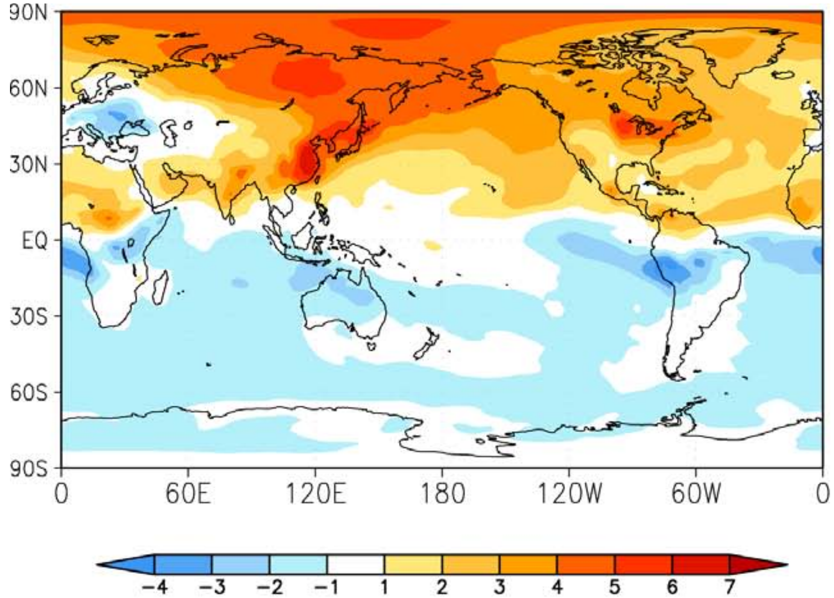


- **In the NH, CO_2(850hPa)>CO_2(400hPa): fossil fuel+ land carbon source;**
- **In the SH, CO_2(850hPa)<CO_2(400hPa): transported from the NH.**

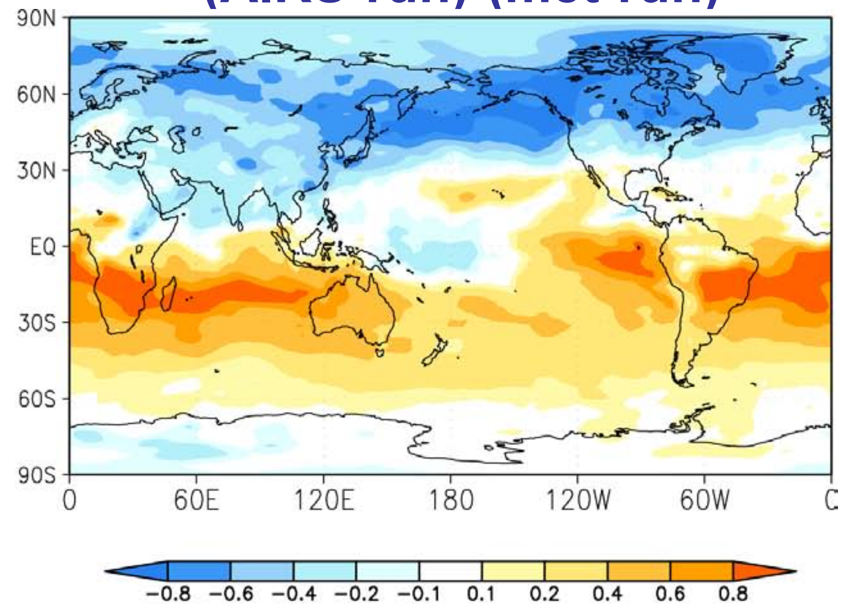
Assimilating CO_2 adjusts CO_2 vertical gradient

May 2003: CO_2(850hPa)-CO_2(400hPa)

Met-run



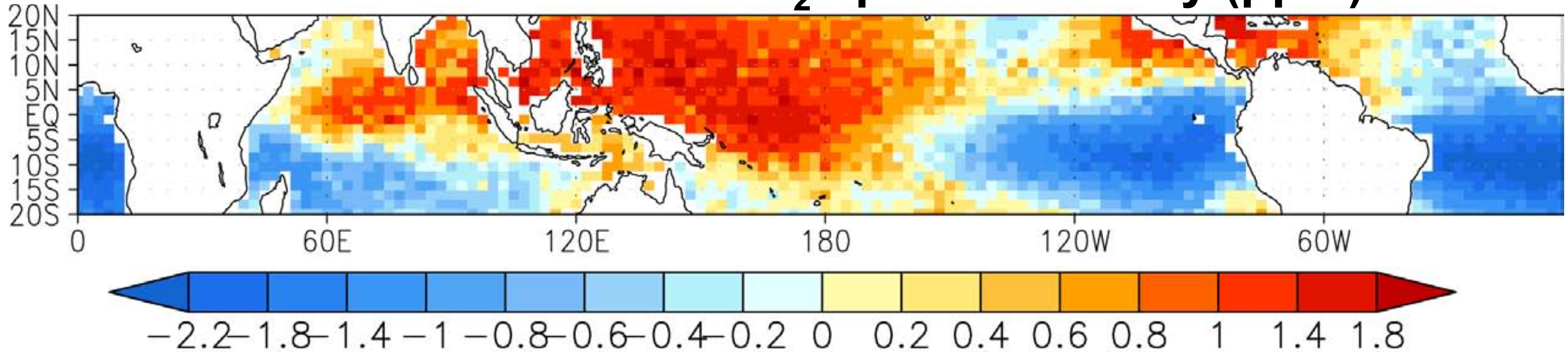
(AIRS-run)-(met-run)



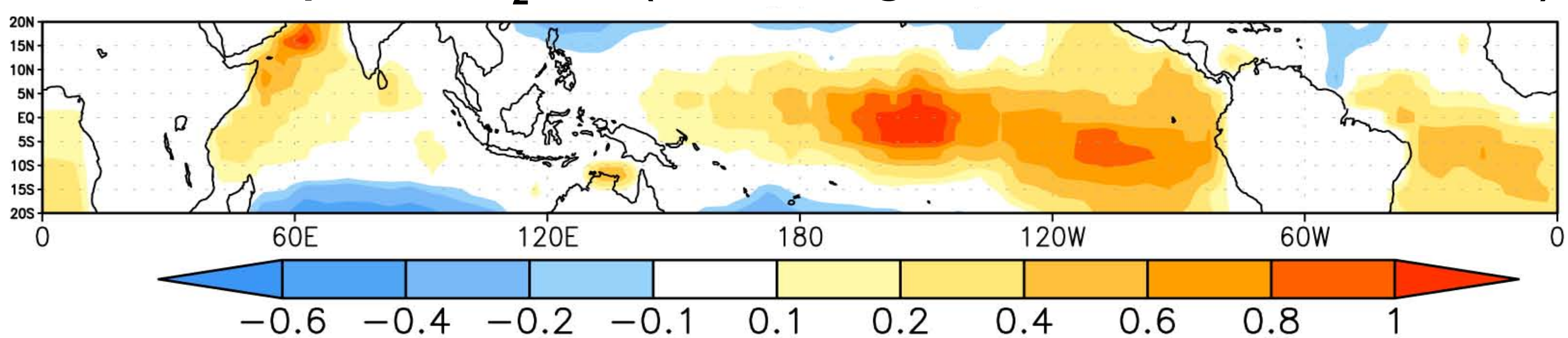
- **In the NH, CO_2(850hPa)>CO_2(400hPa): fossil fuel+ land carbon source;**
- **In the SH, CO_2(850hPa)<CO_2(400hPa): transported from the NH.**
- **Require CO_2 obs in the lower troposphere to further constrain gradient.**

Inconsistent spatial distribution between AIRS CO_2 and ocean-air CO_2 flux

Annual mean AIRS CO_2 spatial anomaly (ppm)

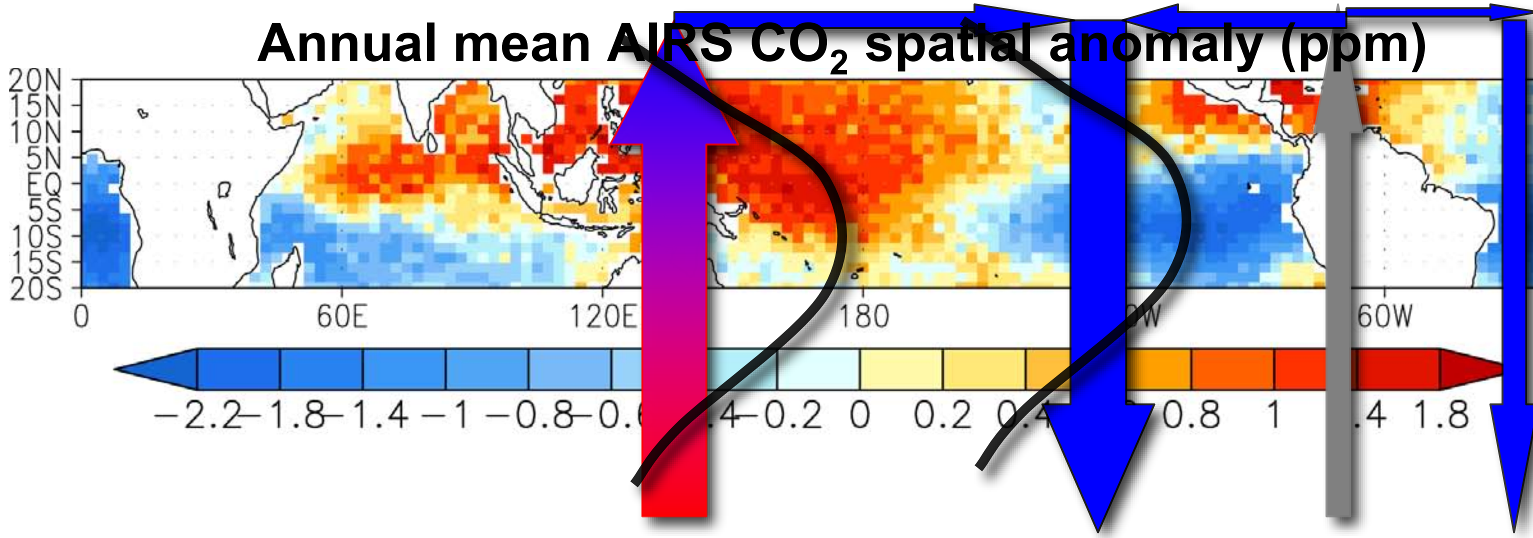


Ocean-atmosphere CO_2 flux (unit: 10^{-9}kgC/m^2/s Takahashi et al., 2002)

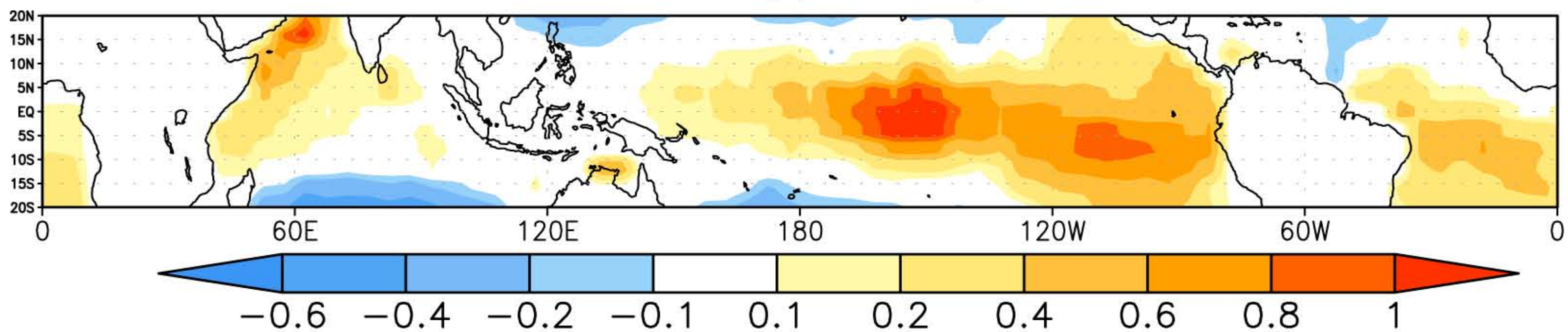


Tropical AIRS CO_2 relates to circulation and averaging kernel

Annual mean AIRS CO_2 spatial anomaly (ppm)

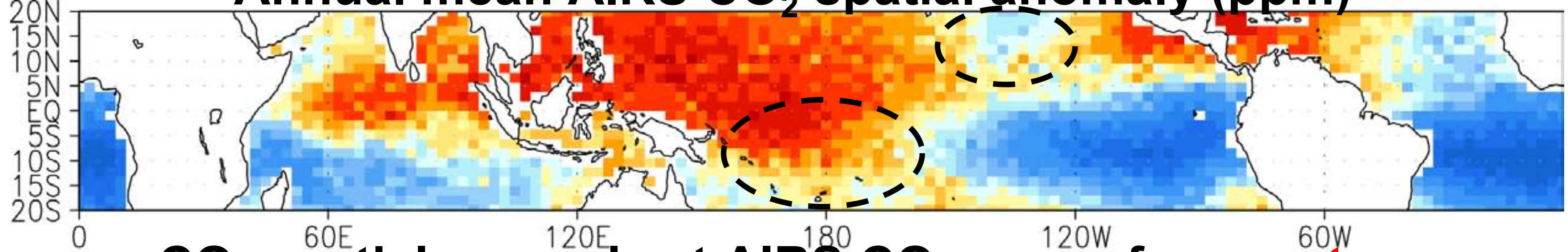


Ocean-atmosphere CO_2 flux (unit: 10^{-9}kgC/m^2/s Takahashi et al., 2002)

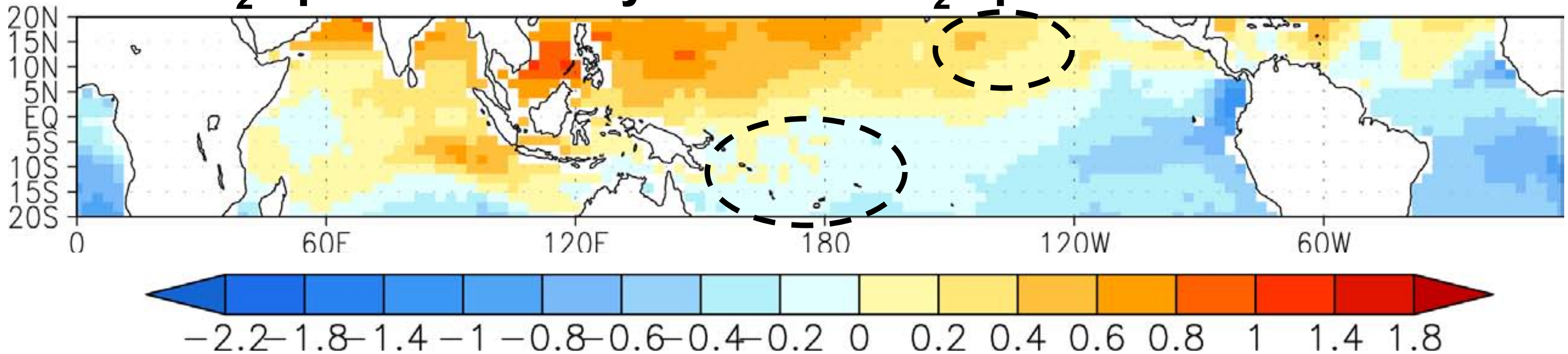


Assimilating AIRS CO_2 improves spatial pattern

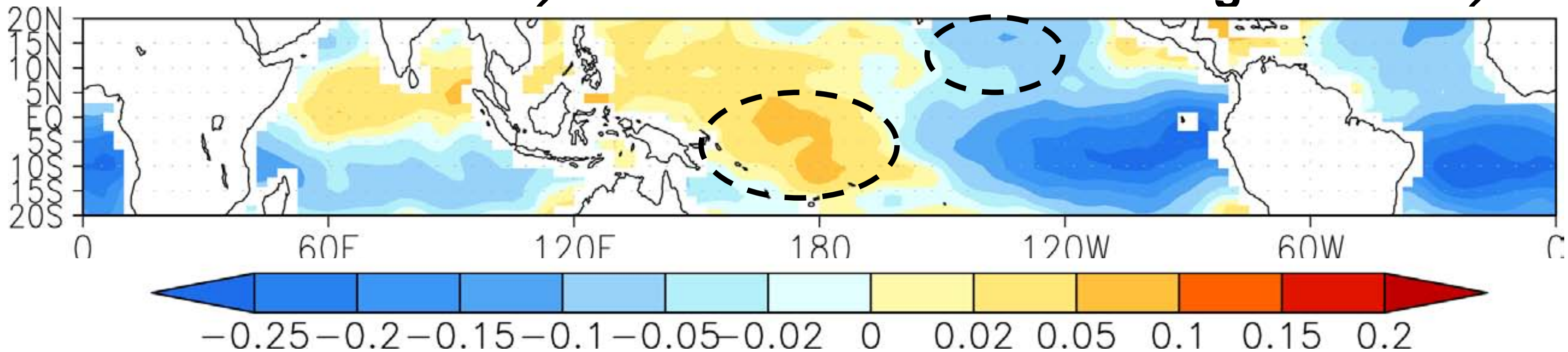
Annual mean AIRS CO_2 spatial anomaly (ppm)



CO_2 spatial anomaly at AIRS CO_2 space from met-run



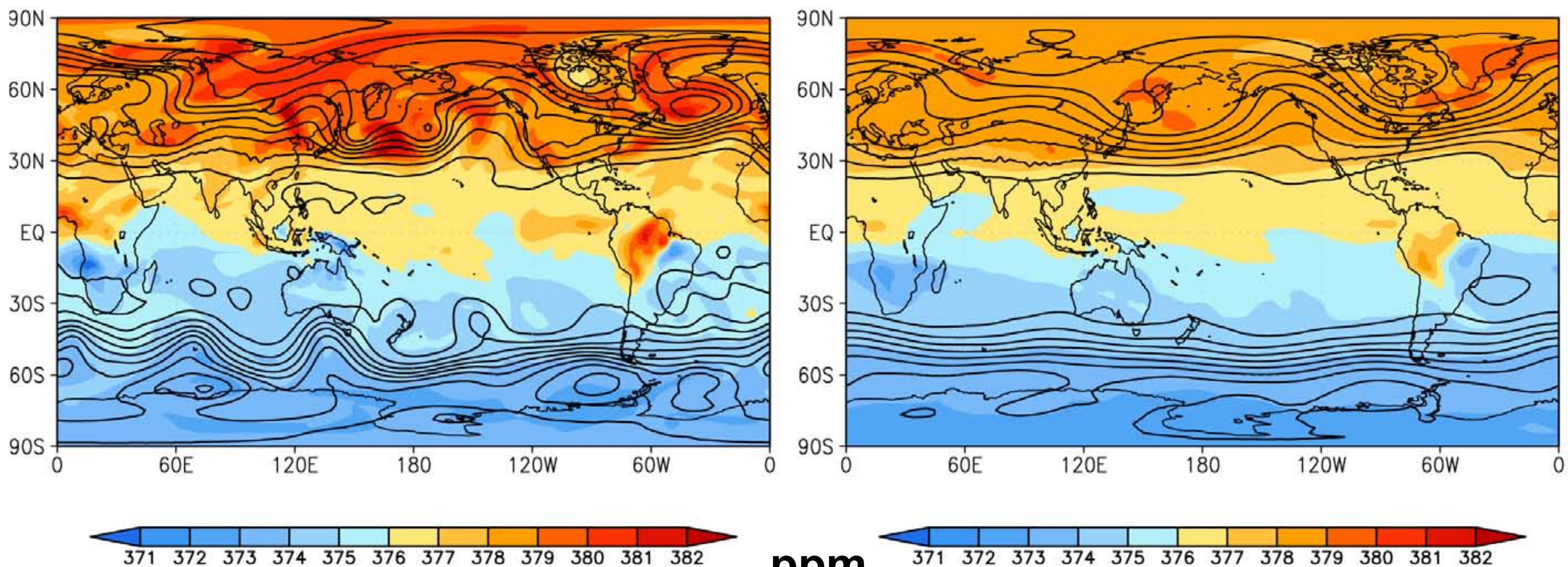
Annual mean CO_2 correction from assimilating AIRS CO_2



Consistent CO_2 distribution and weather pattern

500hPa geopotential height (contour) and CO_2 from AIRS-run (shaded)

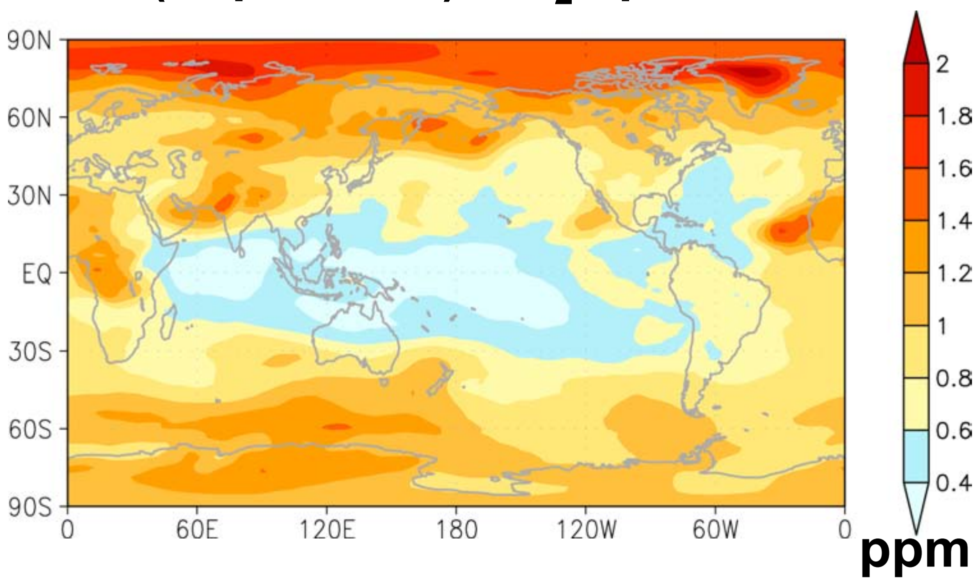
Single time (12Z27Feb2003) **Time average over Feb 2003**



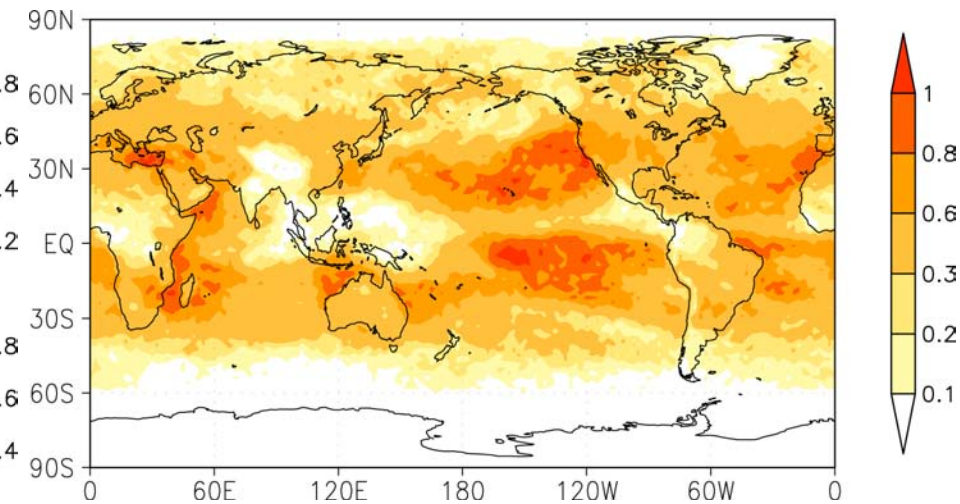
- **Simultaneous assimilation of meteorology variables and CO_2 generates CO_2 distribution consistent with weather pattern**

CO_2 analysis spread ranges from 0.4ppm to 2ppm at 400hPa

400hPa monthly mean (September) CO_2 spread



Average num of CO_2 observations at each grid box within 6 hours



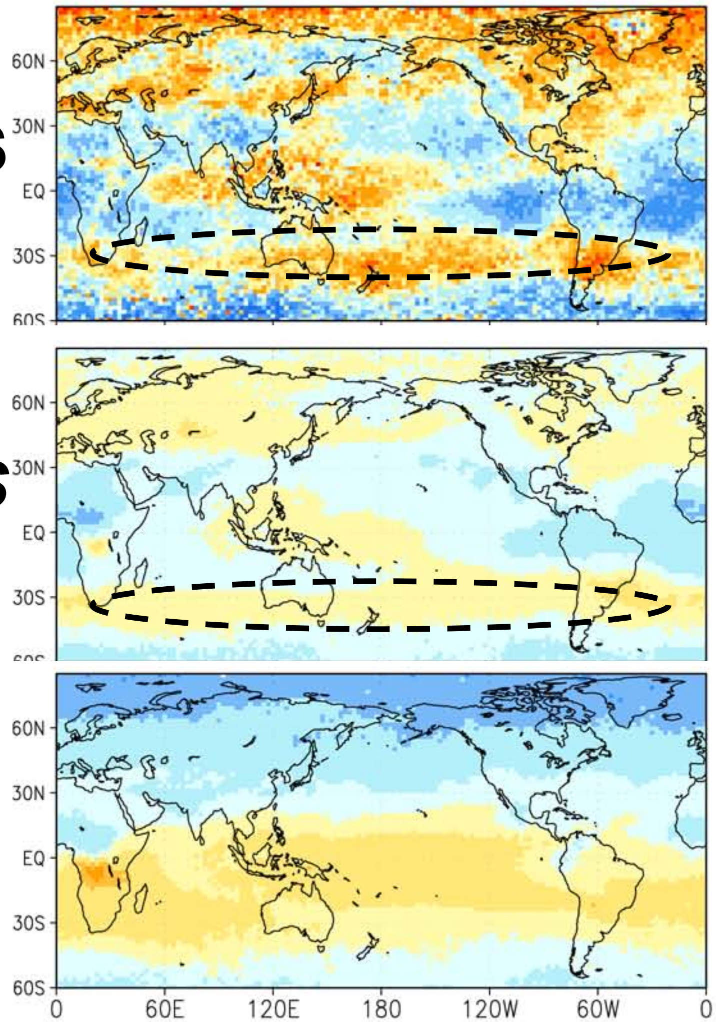
- **Analysis ensemble spread is related to observation coverage, forecast error and observation error;**
- **Larger spread over high latitudes, and over land;**
- **Smaller spread over tropical ocean is due to observation coverage and propagation through forecast.**

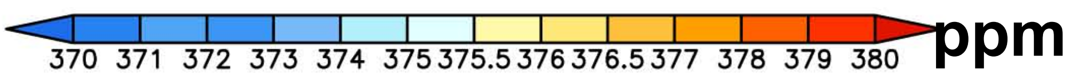
Column-integrated CO_2—Sep

AIRS

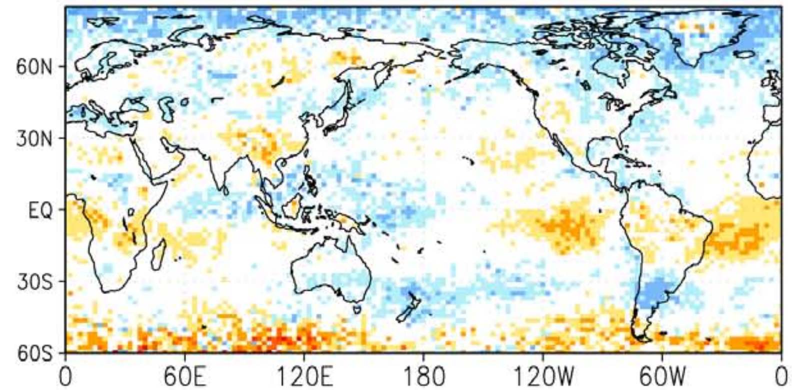
AIRS-run

Met-run

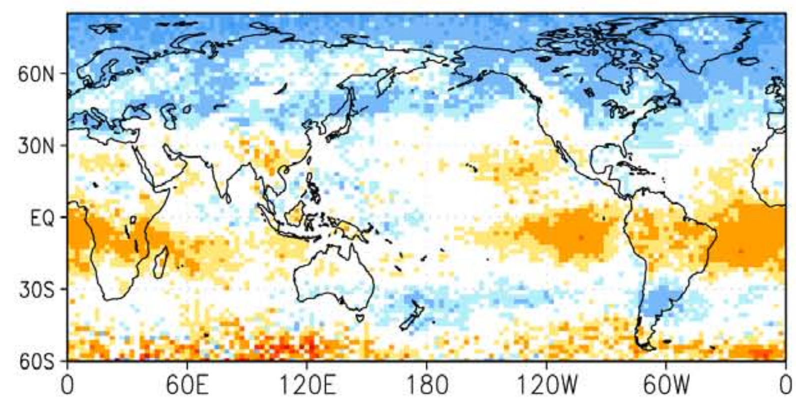


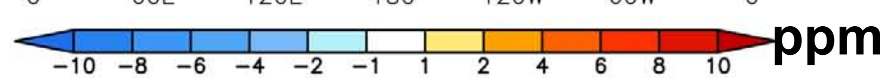


AIRS-run **- AIRS**

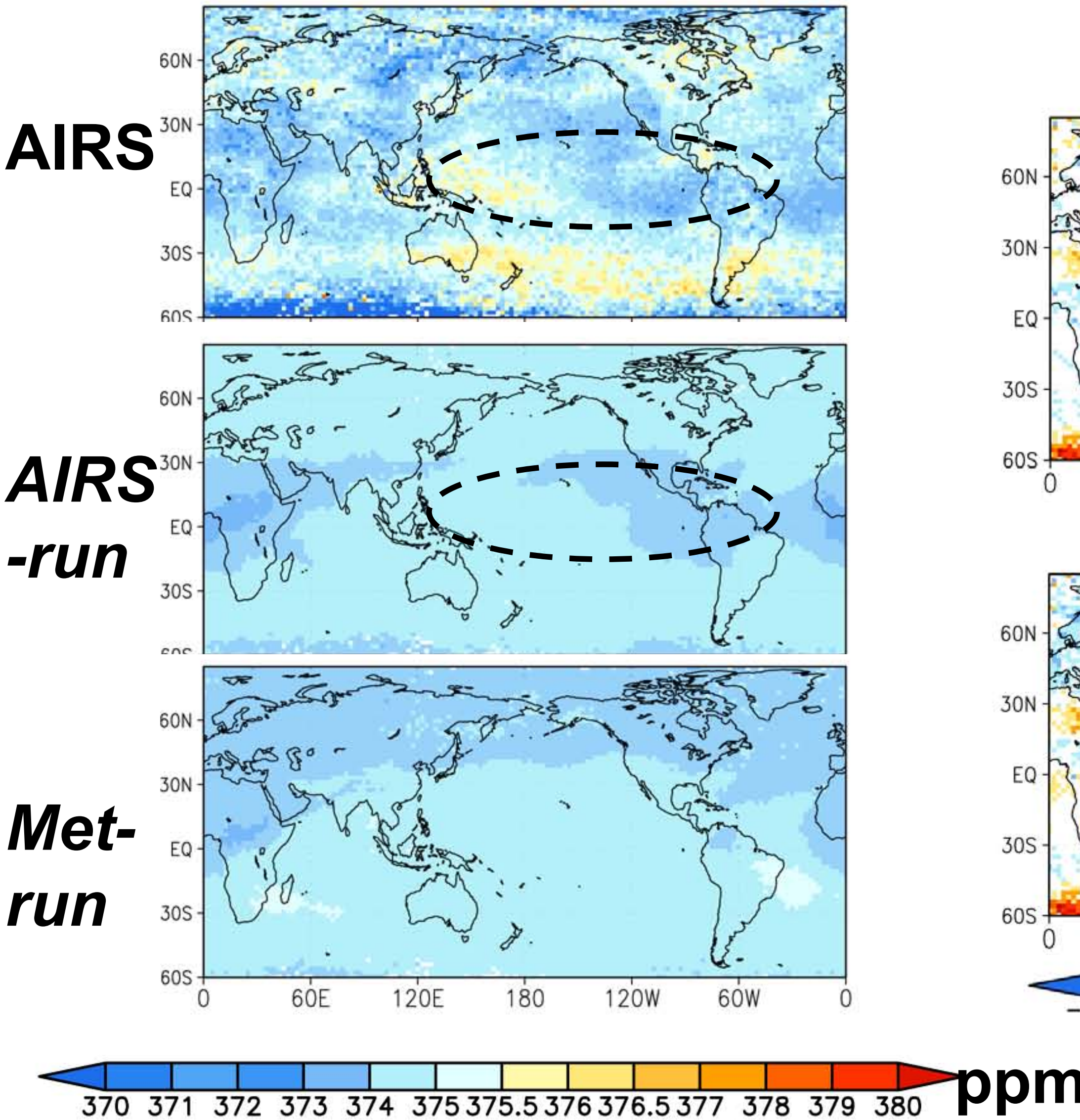


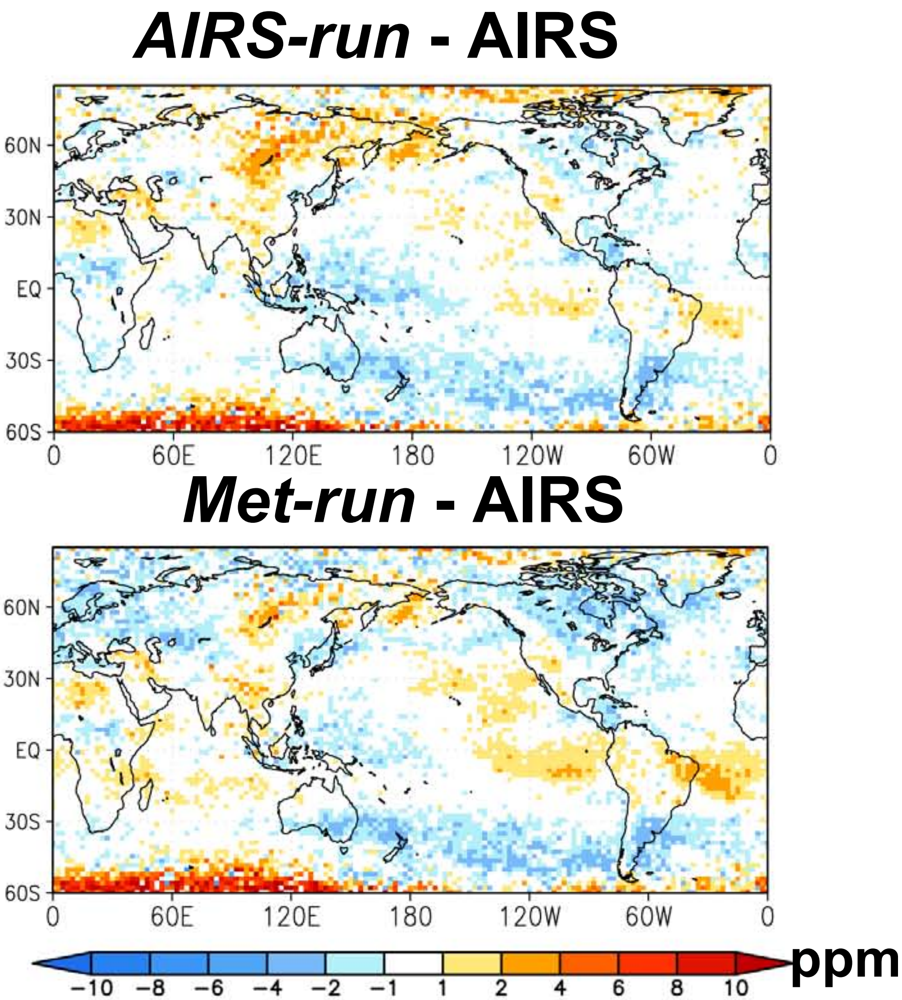
Met-run **- AIRS**





Column-integrated CO_2—Oct



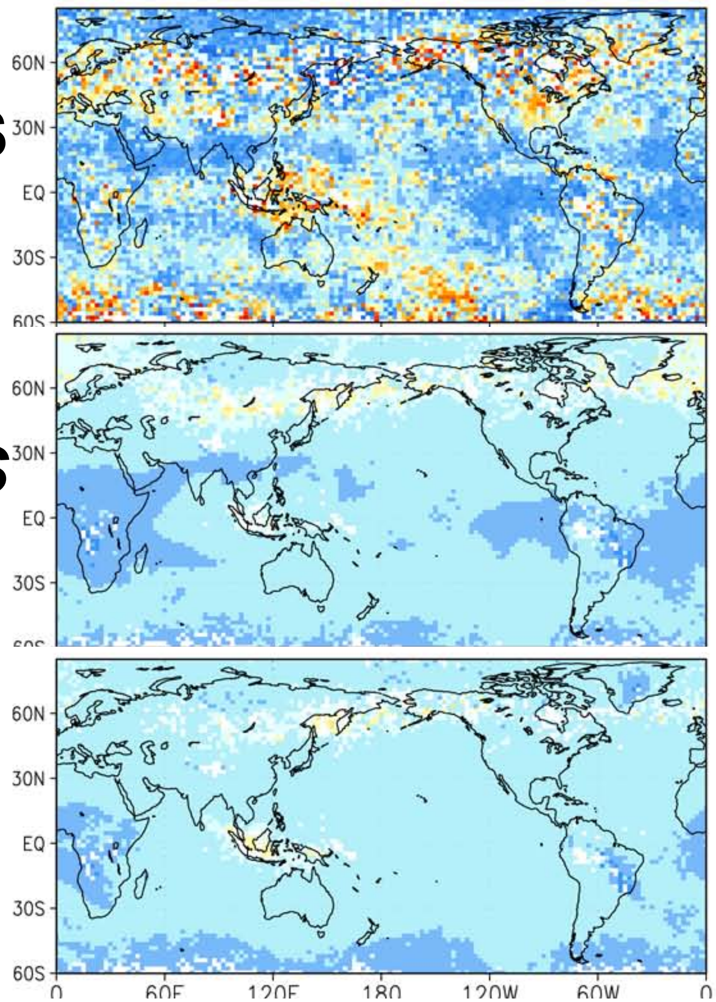


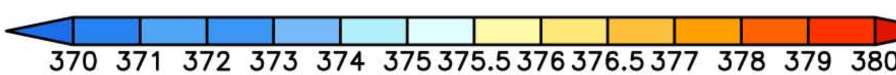
Column-integrated CO_2—Nov

AIRS

AIRS-run

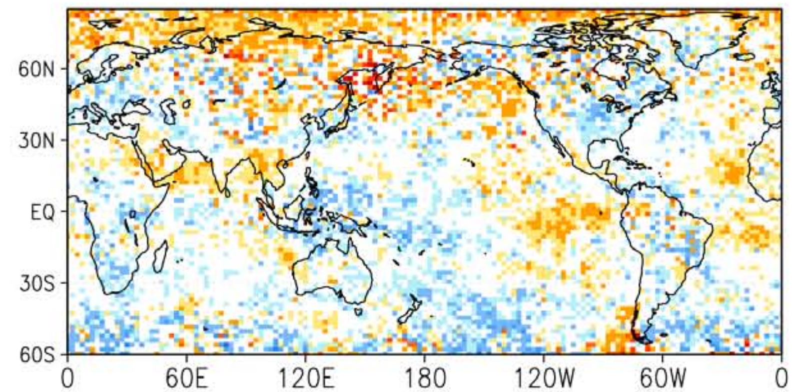
Met-run



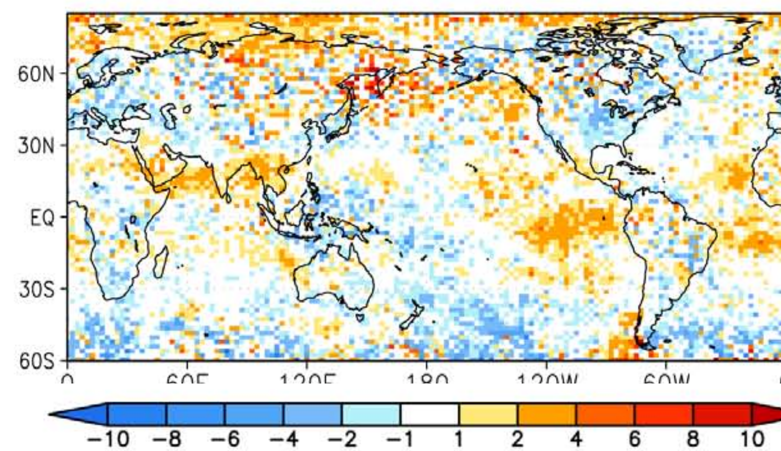


ppm

AIRS-run - AIRS



Met-run - AIRS



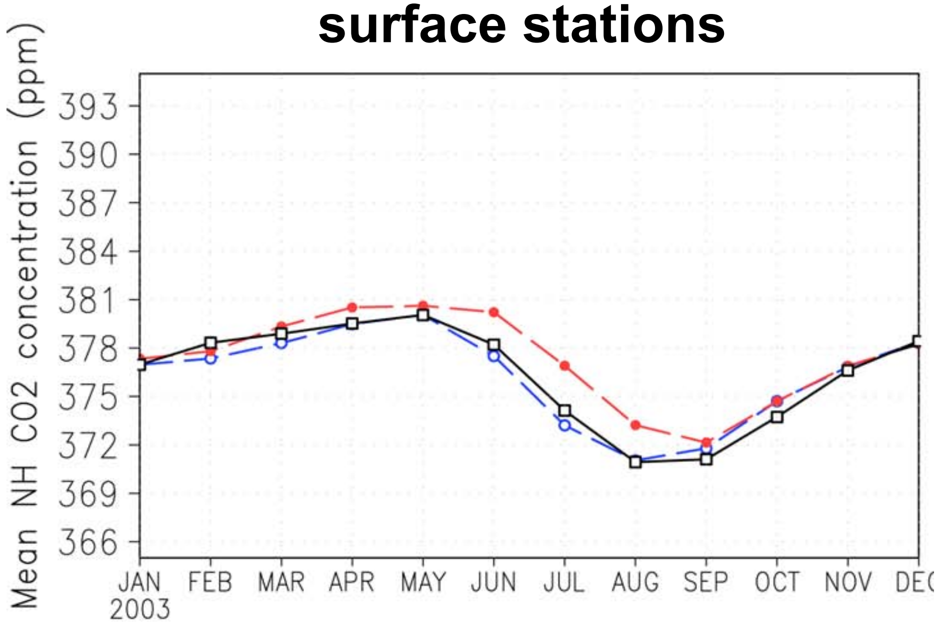
ppm

20 days with no AIRS CO2

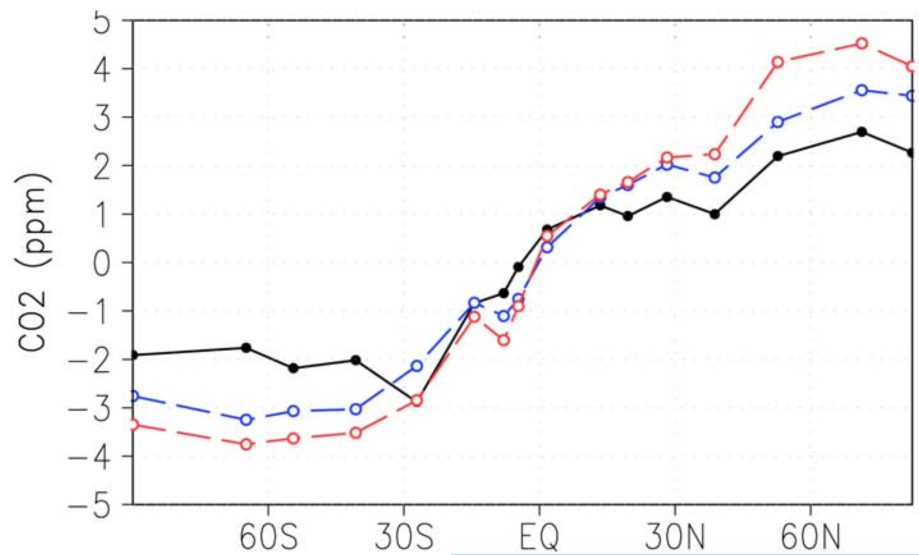
Assimilating AIRS CO_2 improves surface CO_2 seasonal cycle and the N-S gradient

Surface obs: black; Met-run: red: AIRS-run: blue

Mean NH CO2 concentration at 8 surface stations



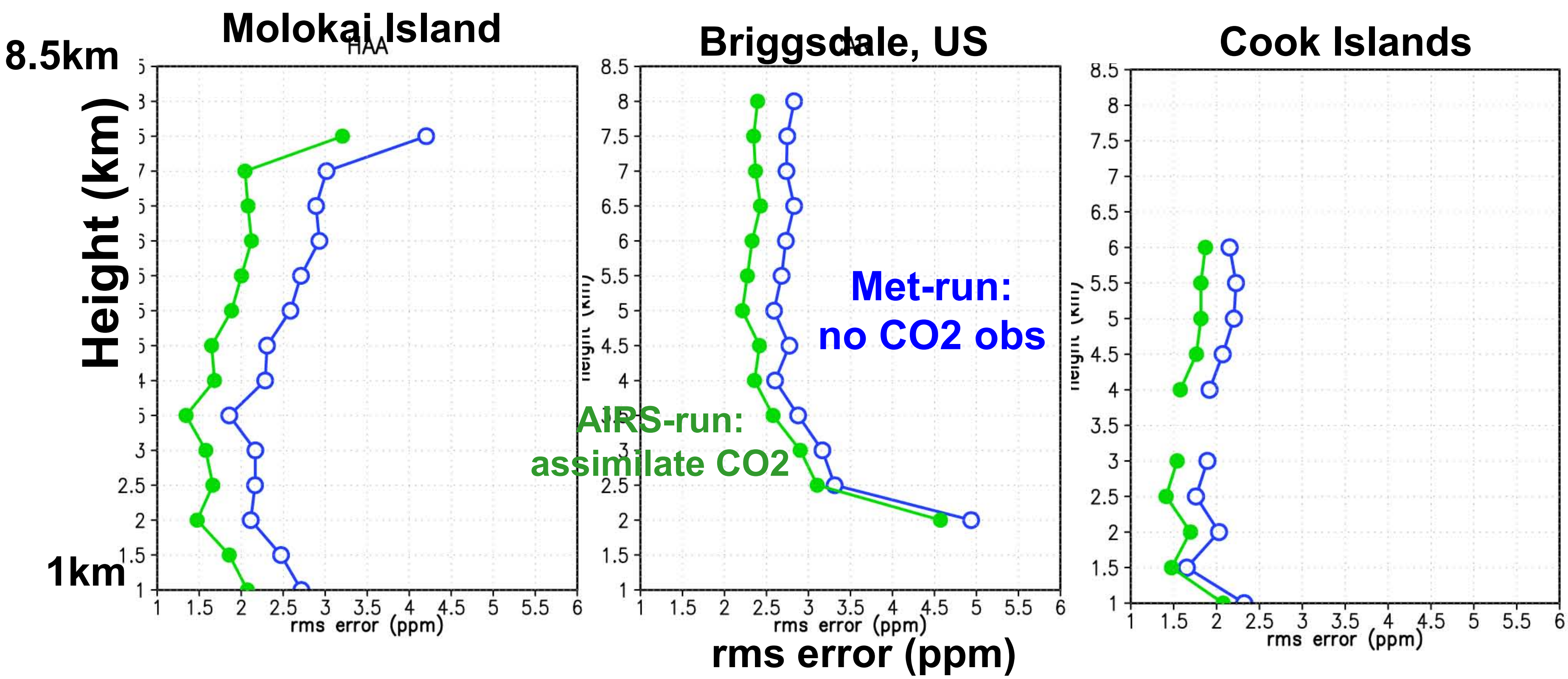
The N-S gradient based on 16 surface stations



Surface data is from NOAA/ESRL website

Met-run has similar NH CO2 concentration and the N-S gradient

Assimilating AIRS CO_2 improves CO_2 state estimate

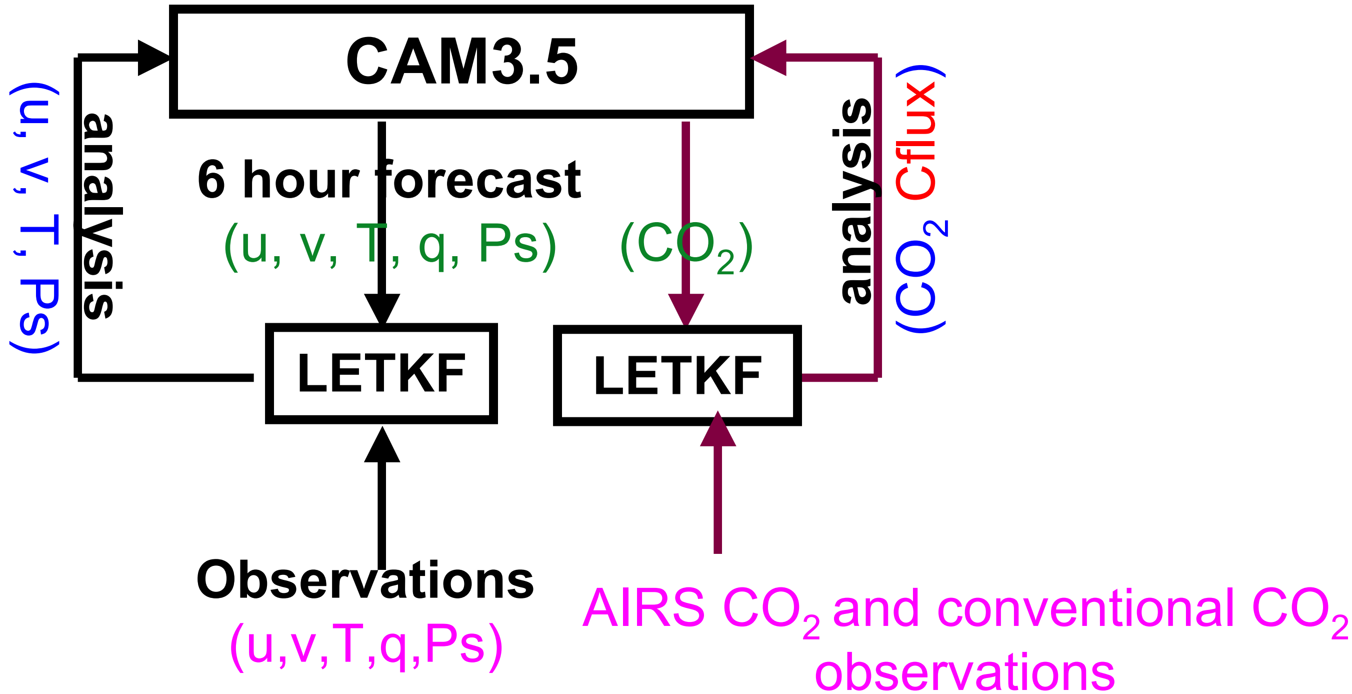


Verified against independent aircraft CO_2 observations

- CO_2 from the AIRS-run can be about 1 ppm more accurate than those from the met-run.

Preliminary results on surface carbon flux estimation by assimilating AIRS CO2

The impact of AIRS CO_2 assimilation on surface CO_2 flux

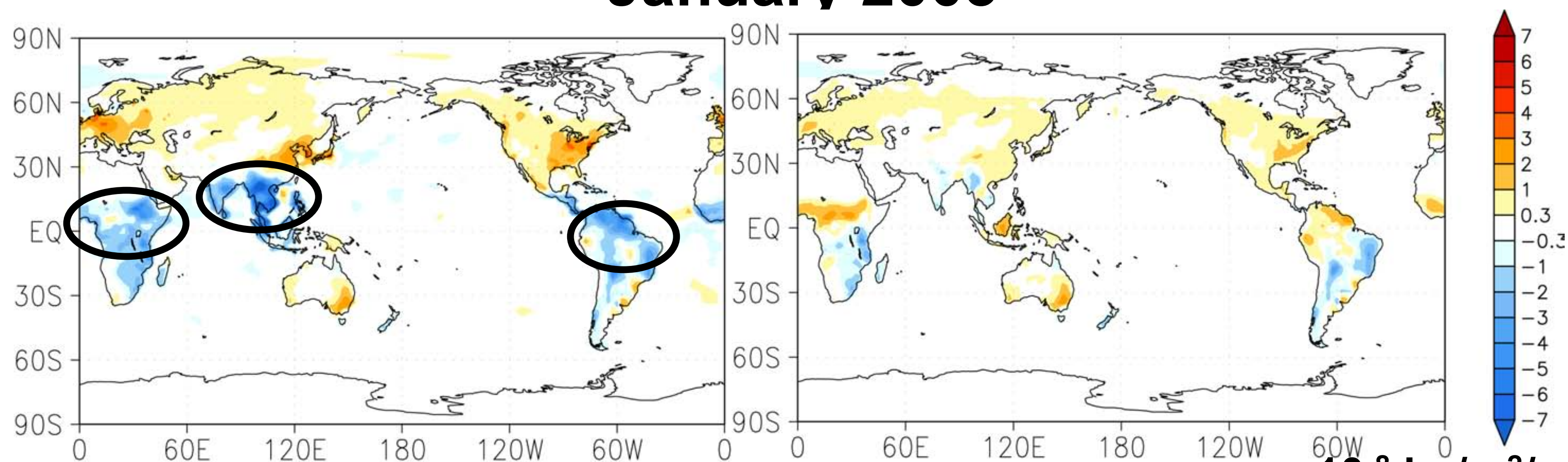


LETKF: Local Ensemble Transform Kalman Filter (Hunt et al., 2007)

- **The carbon flux analysis acts as boundary forcing for the forecast of next time step.**
- **Four and a half months assimilation cycles (01Jan2003-10May2003).**

Carbon Flux Analysis:Data Assim (left) Carbon Flux (CASA (land)+Takahashi (ocean))(right)

January 2003

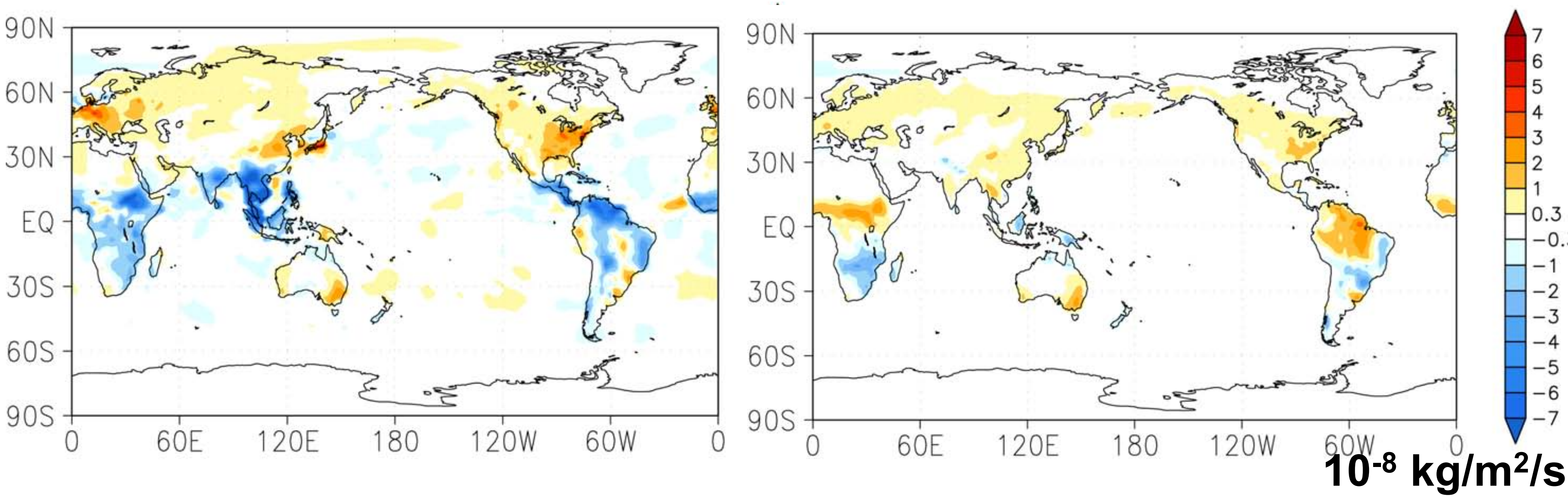


10^{-8} $kg/m^2/s$

- AIRS has the most impact over the tropical land
- Stronger source in the NH winter
- Stronger sink in the tropics and SH subtropics
- Noisy over ocean compared to Takahashi

Carbon Flux Analysis:Data Assim (left)
Carbon Flux (CASA (land)+Takahashi (ocean))(right)

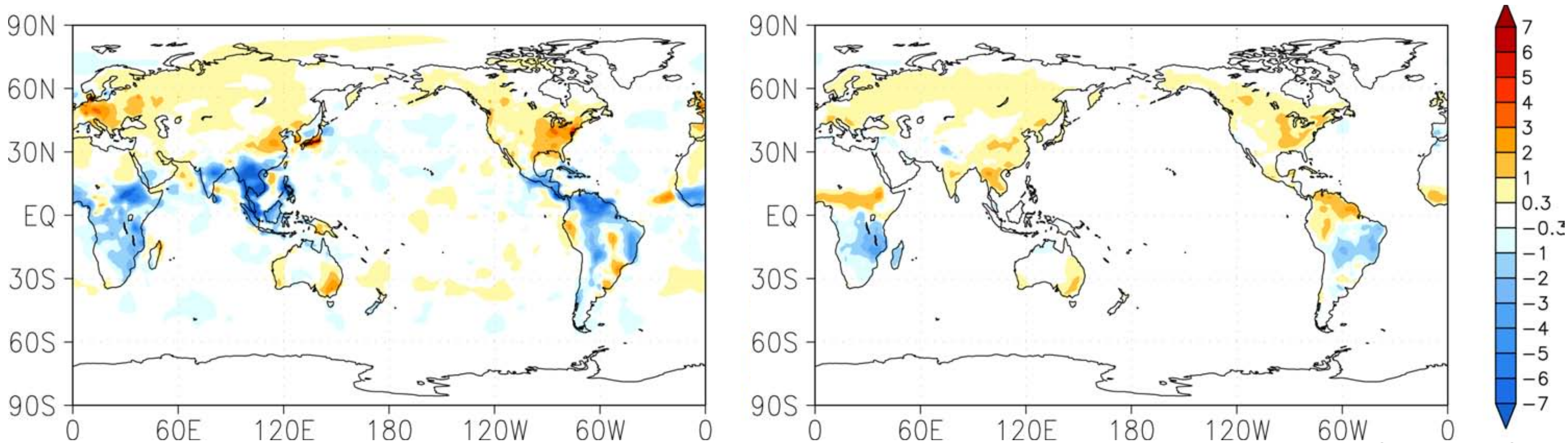
February 2003



- **Stronger source** in the NH winter
- **Stronger sink** in the tropics and SH subtropics
- **Noisy over ocean compared to Takahashi**

Carbon Flux Analysis:Data Assim (left)
Carbon Flux (CASA (land)+Takahashi (ocean))(right)

March 2003

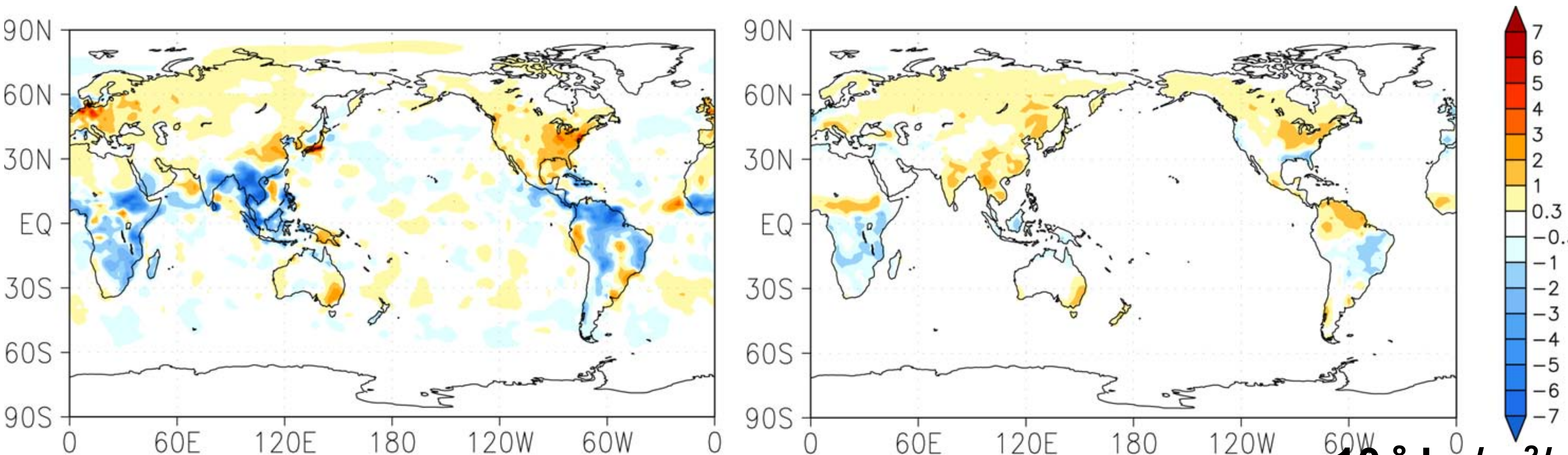


10^{-8} kg/m²/s

- **Little change**

Carbon Flux Analysis:Data Assim (left)
Carbon Flux (CASA (land)+Takahashi (ocean))(right)

April 2003

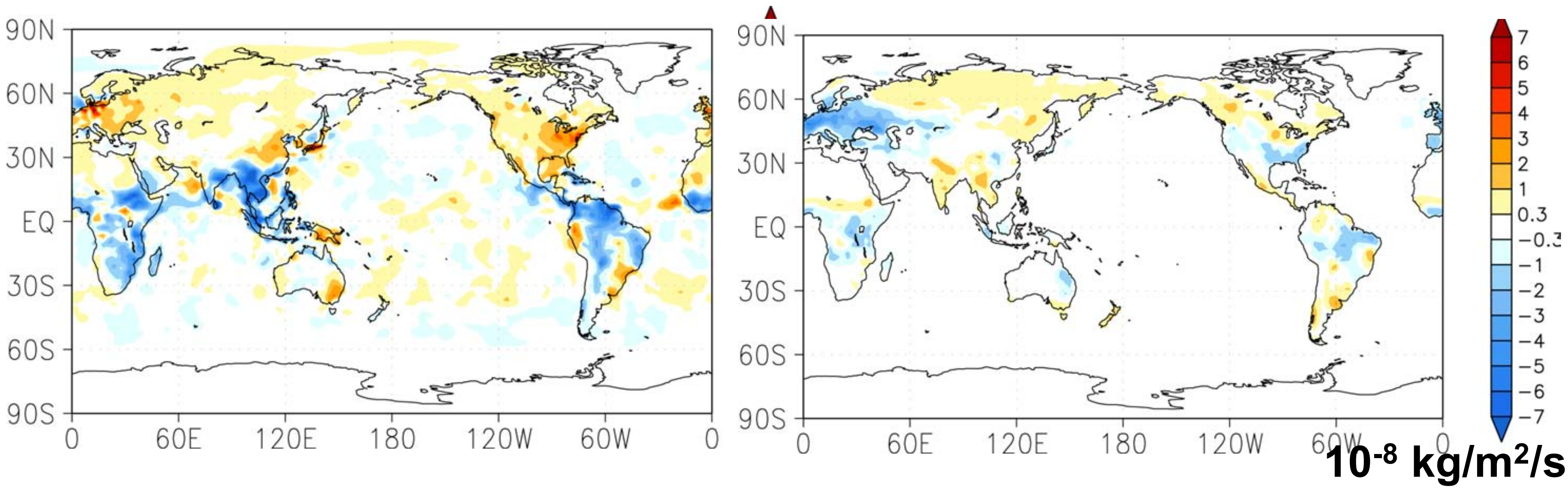


10^{-8} kg/m^2/s

- **Little change**

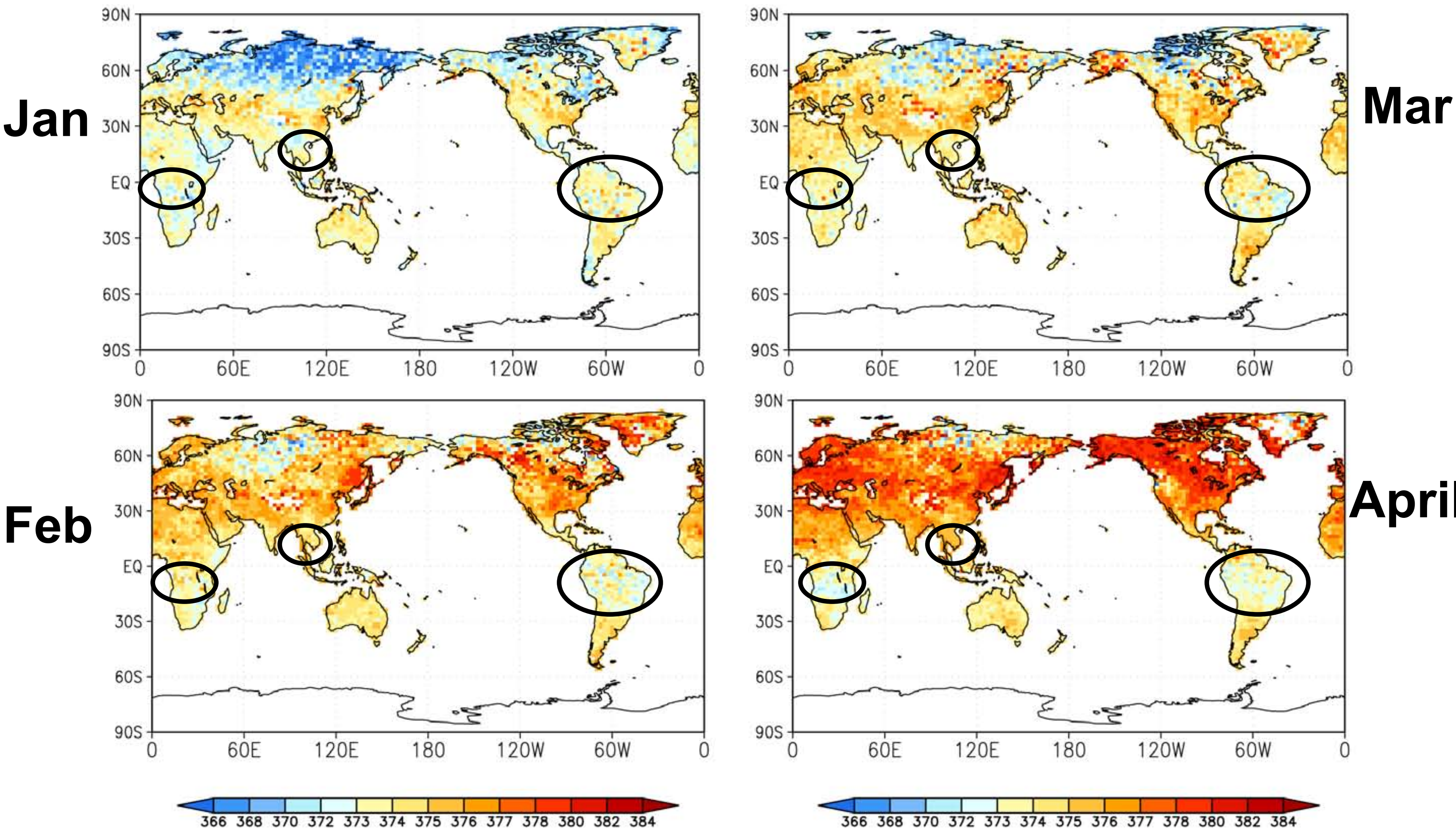
Carbon Flux Analysis:Data Assim (left)
Carbon Flux (CASA (land)+Takahashi (ocean))(right)

May 2003



• **As in the OSSEs, the surface fluxes appear initially to be reasonable and then they “get stuck”.**

Monthly average AIRS CO_2 does not change much over the tropical land from January to May



Conclusions - General

- **EnKF brings important advantages for Reanalysis:**
  - ✓ **Analysis uncertainty**
  - ✓ **Adaptation to new observing systems**
  - ✓ **Estimation of obs. errors and identification of bad observations (not shown)**
  - ✓ **Estimation of model bias (essential)**
- **For Carbon Reanalysis it is essential to assimilate at the same time meteorological and carbon observations**

Conclusions - Simulations (OSSEs)

- The advantage of the OSSEs is that we know the true fluxes and CO_2
- It is possible to estimate surface carbon fluxes from atmospheric CO_2 measurements but
  - ✓ Need "variable localization" to reduce sampling errors
  - ✓ Need adaptive inflation of the B error covariance
  - ✓ Need to estimate model bias
- Problem: the initial results after spinup from random fields are good, but then the surface fluxes "don't want to change anymore".
  - ✓ This is probably due to model bias

Conclusions - AIRS data assimilation

- **AIRS CO_2 data assimilation is clearly successful!**
  - ✓ **Improved atmospheric CO_2 and N-S gradient**
  - ✓ **Better agreement with independent observations**
  - ✓ **Insight about vertical circulation and mixing**
- **Preliminary estimations of carbon fluxes are very promising after one month spin-up:**
  - ✓ **Compared with CASA fluxes they yield reasonable uptakes in the SH summer and stronger emissions in the NH winter**
  - ✓ **But, like in the OSSEs, the fluxes "don't want to change" with season**

Conclusions - AIRS/IASI GoSAT/OCO2

• The combination of satellite and in situ data is important:

- ✓ Results are more accurate in NH than in SH

• We need more near surface information

- ✓ Carbon fluxes can be derived from atmospheric CO2

• Results depend on optimal forecast spread, a difficult problem for surface fluxes:

- ✓ Work on estimating model bias
- ✓ Should find why after initial good surface fluxes they "don't want to change" with season
- ✓ We probably need to estimate diurnal and seasonal changes with a different approach (e.g., EOFs).